Imaging and Monitoring with Seismic Coda Waves

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Mini-Colloque 19

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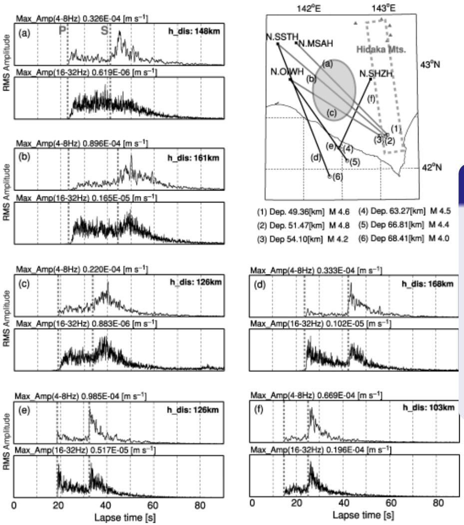
Crustal Coda Waves

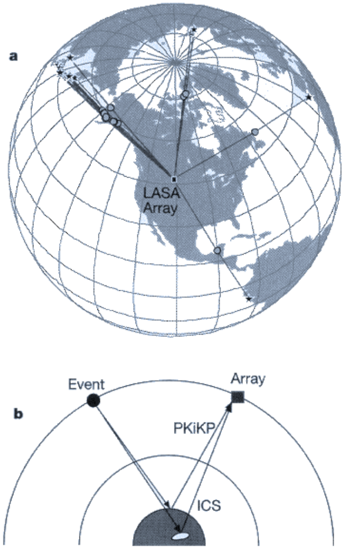


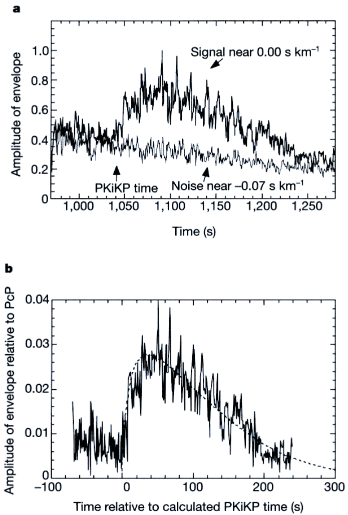
Earthquakes in Japan

Space and Time Scales

- Frequency > 1 Hz
- Wavelength $\sim$ tens of meters to kilometers
- Model: radiative transfer
- Mean free path 0.1–1000 kms

Inner Core Coda Waves





Vidale and Earle, Nature (2000)

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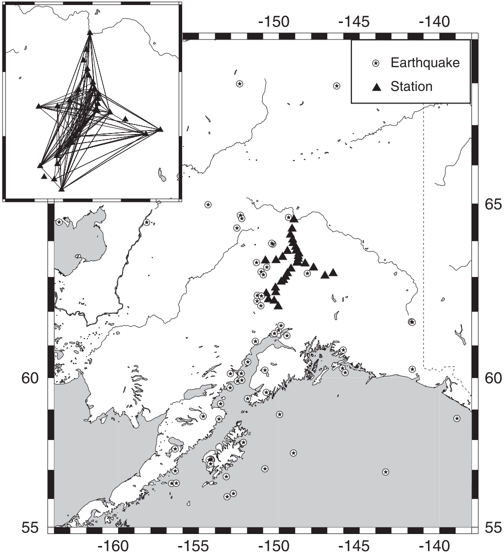
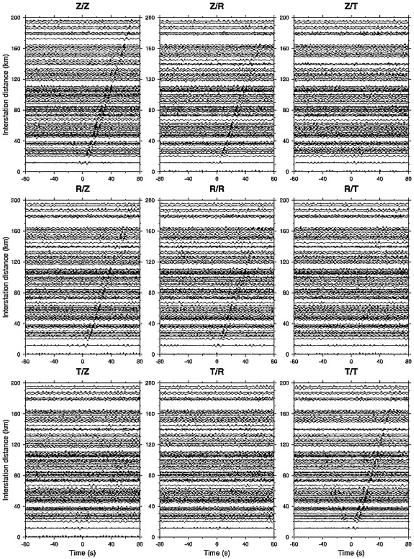
Experimental Set-Up



Cross-correlation of coda waves



- $C_{ij}(\mathbf{x}_a, \mathbf{x}_b, \tau) = \int u_i(\mathbf{x}_a, t - \tau/2) u_j(\mathbf{x}_b, t + \tau/2) dt$
- Source average
- Reconstruction of Rayleigh and Love waves fundamental mode
- Temporal asymmetry

Underlying physics: Transport theory in random media

Asymptotic solution of Bethe-Salpeter equation

Correlation of two Green functions:

$$\Gamma(\mathbf{x}, \mathbf{r}; t, \tau) = \langle G(\mathbf{x} + \mathbf{r}/2, t + \tau/2) G(\mathbf{x} - \mathbf{r}/2, t - \tau/2)^* \rangle$$

Fourier transform over τ:

$$C(\mathbf{x}, \mathbf{r}; t, \omega) = \int \Gamma(\mathbf{x}, \mathbf{r}; t, \tau) e^{i\omega\tau} d\omega$$

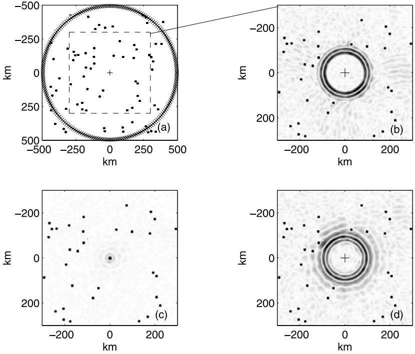
Asymptotic result $t \to \infty$

$$C(\mathbf{x}, \mathbf{r}; t, \omega) \sim \frac{\mathrm{e}^{-x^2/4Dt - \omega t/Q_i}}{(Dt)^{3/2}} \mathrm{Im} \langle G(\mathbf{r}, \omega) \rangle$$

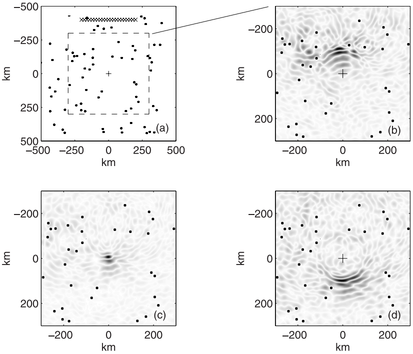
Barabanenkov & Ozrin, Phys Lett. A, 1991

Understanding the temporal asymmetry

Perfect source distribution



Imperfect source distribution



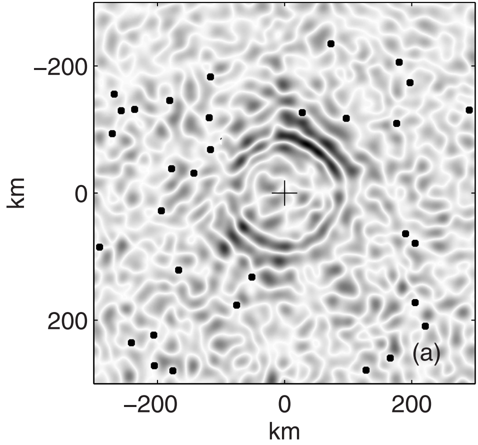
$$\frac{d\langle u(\mathbf{x}-\mathbf{r}/2,t-\tau/2)u(\mathbf{x}+\mathbf{r}/2,t+\tau/2)\rangle}{d\tau} \propto$$

$$E(\mathbf{x},t)\left[G(\mathbf{r},\tau)-G(\mathbf{r},-\tau)\right]-3J(\mathbf{x},t)\cdot\nabla_{\mathbf{r}}\left[G(\mathbf{r},\tau)-G(\mathbf{r},-\tau)\right]$$

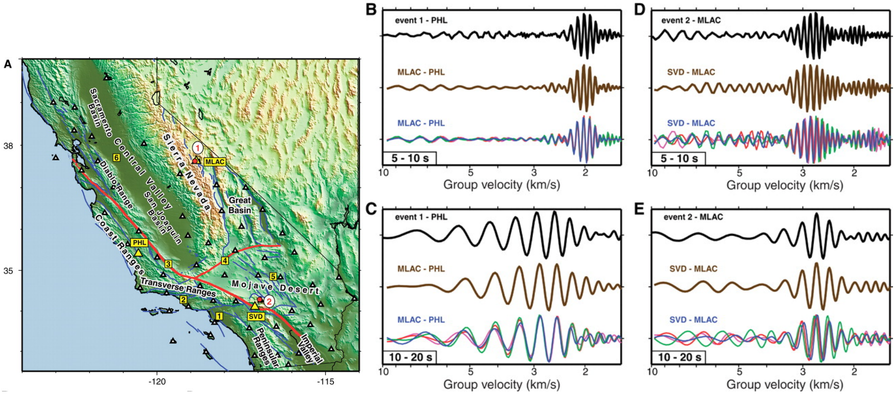
(B.V.T., PRL, 2003; Paul et al., J.G.R., 2005)

Role of multiple scattering and Equipartition

Imperfect Source Distribution + Late Coda



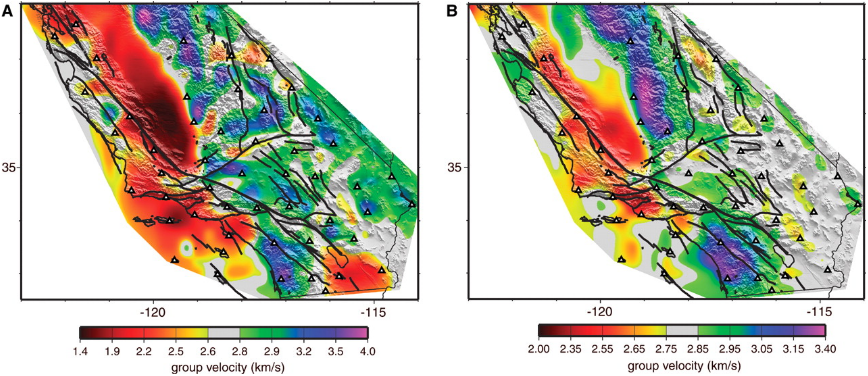
GF reconstruction from ambient noise



Comparison of 'ground truth' Green's function and cross-correlation of noise wavefields recorded at 3 seismic stations

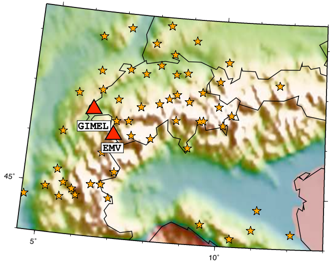
(Shapiro et al., Science, 2005)

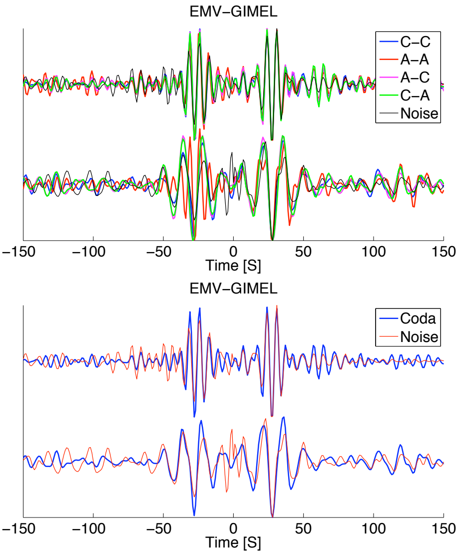
Noise-based Tomography



Group velocity maps at 5-10s and 10-20s

GF reconstruction with the coda of noise based GF





Stehly et al., J.G.R., 2008

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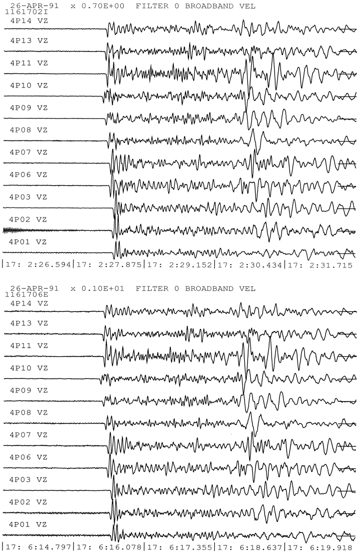
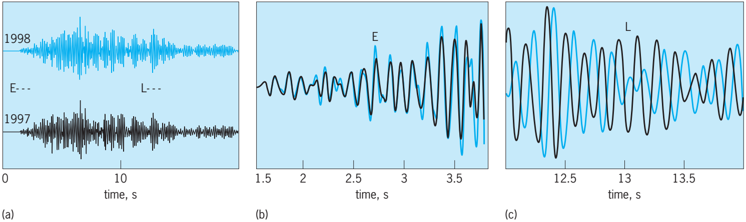
Earthquake doublets



- Same location
- Same mechanism
- Nearly identical waveforms
- Drawback: no continuous monitoring

Repeated shots recorded on Merapi Volcano

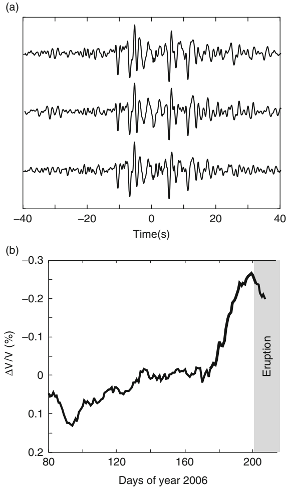


- No changes on the first arrival
- Increasing delay time in the coda

  Stretching of the signal ≈ tiny velocity change in the medium
- Active source experiments are expensive

Monitoring with seismic noise

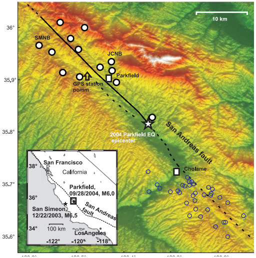
Example on Piton de la Fournaise

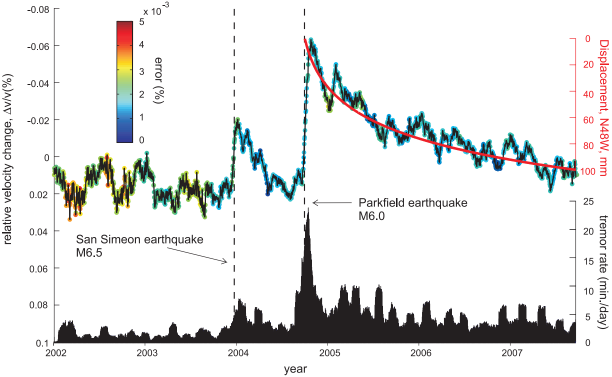


- Green function obtained from cross-correlation of seismic noise
- Measurement of stretching parameter in the coda

"Passive image interferometry" (Sens-Schoenfelder and Wegler, GJI, 2006; Brenguier et al., Nature Geoscience, 2008; Brenguier et al., Science, 2008)

Application to fault zones



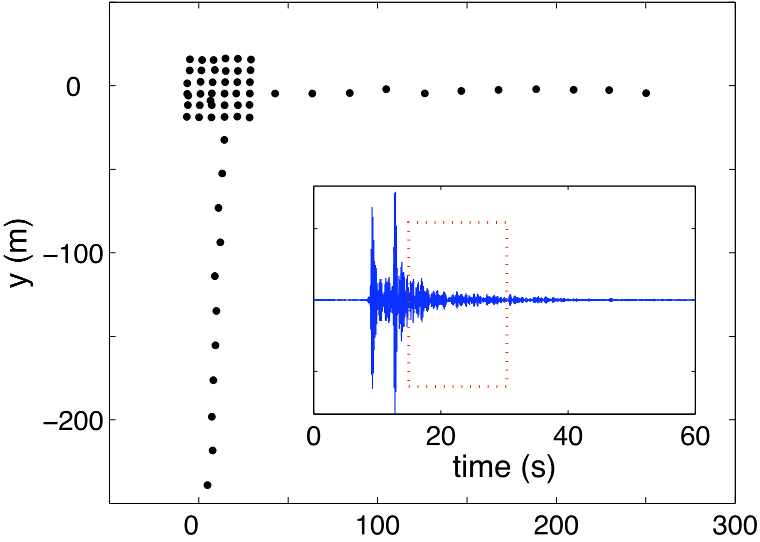


Brenguier et al., Science, 2008

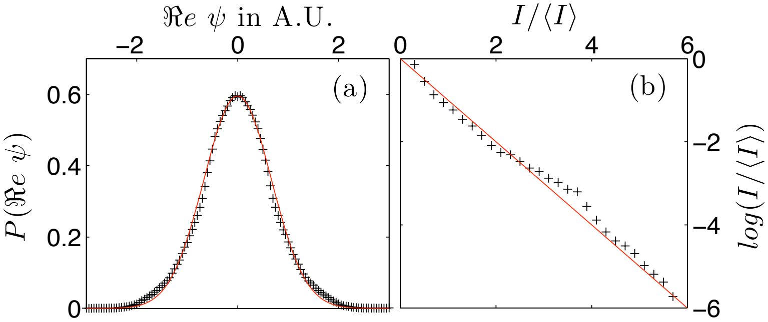
Phase Statistics

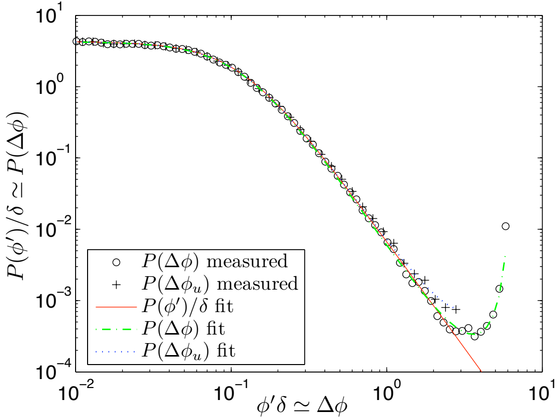
- Phase of the analytic signal
- Easy with seismic waves: spatial and temporal resolution
- Free from effect of absorption
- Simplifying assumptions :
  Analyze the phase field of vertical components
  Wavefield obeys Circular Gaussian Statistics:

Data from California



Field and Intensity

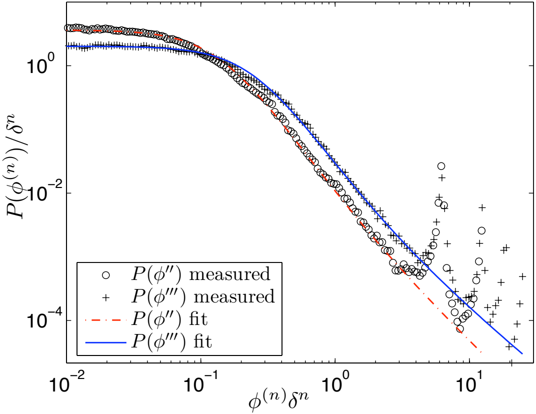




$\Delta\phi$: Phase difference $\in (-2\pi, 2\pi]$

$\Delta\phi_u$: Unwrapped phase difference $\in (-\pi, \pi]$

Higher Phase Derivatives



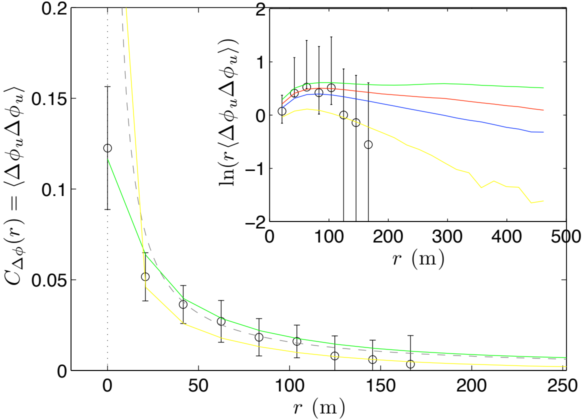
Fitting Parameters:

Coefficients of Taylor series of field correlation function

Universal behavior for n^{th} derivative:

slope $= -(1 + 2/n)$

Phase Difference Correlation



Correlation function $\approx \frac{1}{r} e^{-r/2\ell}$

Van Tiggelen et al., *EPL*, 2006; Anache et al., *P.R.L.*, 2009